

CALIBRATION TECHNIQUES FOR IMAGING FTIR DATA

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Introduction

Some Advantages of ideal imaging FTS's:

- Spectral resolution can be varied easily
- High light throughput
- One-sided interferograms reduce the data storage requirements
- Imaging over time allows analysis of moving objects in the scene.

Problems of ideal imaging FTS's:

- Larger photon background noise
- Large dynamic range of center-burst

Problems with real imaging FTS data [Beer, Bennett]:

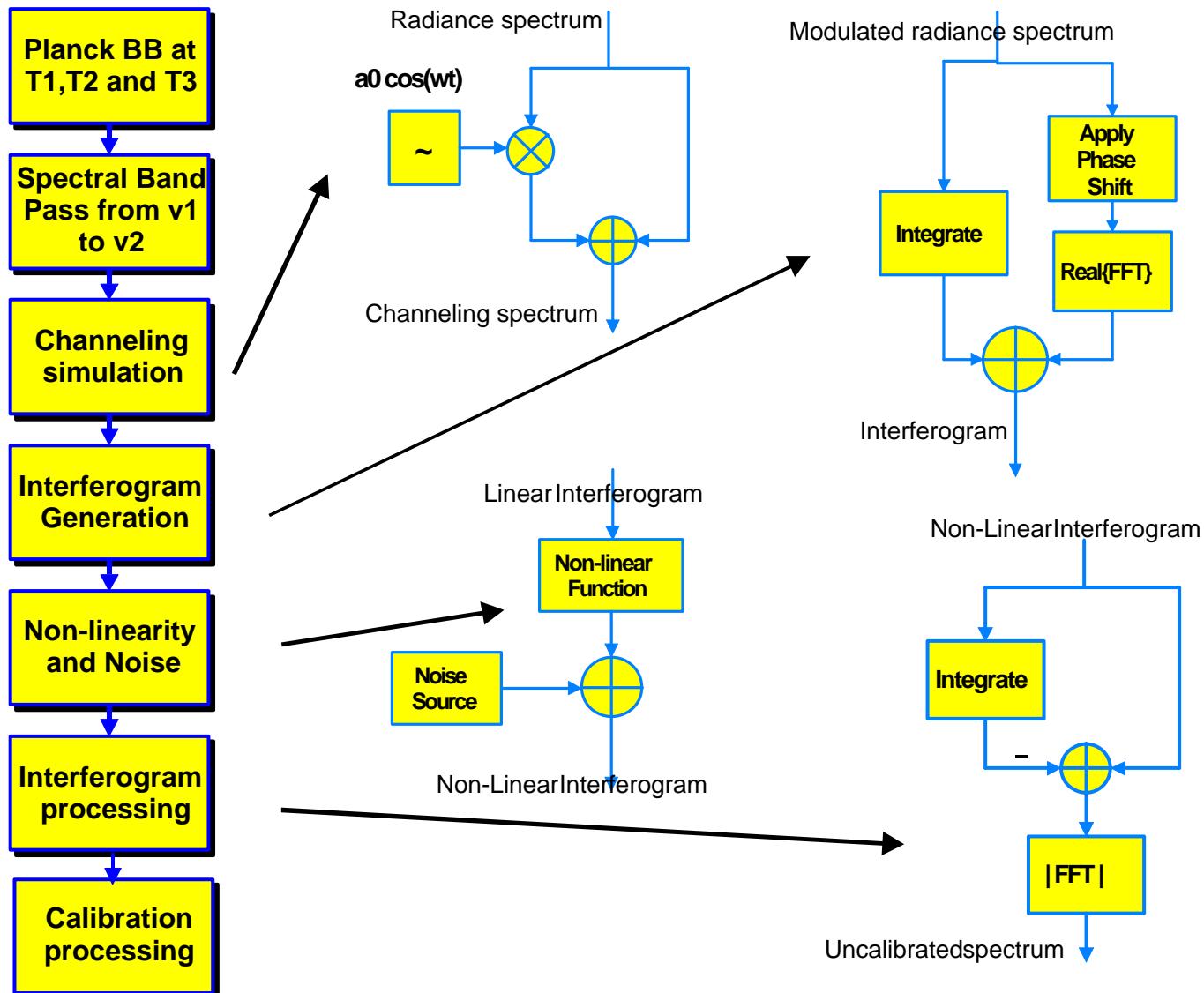
- Phase errors from frequency dependent path differences broaden the center-burst
- Center-burst of a FTS with phase errors is asymmetric requiring full two-sided interferograms
- Pointing jitter smears out spatial information

- Channeling caused by internal reflections
- Non-linear detector response cause systematic temperature offsets
- Random or periodic sampling position errors coupled with non-linearity cause systematic and random temperature errors
- Dead or noisy pixels must be corrected before pointing jitter can be removed

Solutions to real-world problems:

- Dispersion reduces the dynamic range of center-burst → fewer quantization levels [Griffiths and de Haseth]
- Phase corrections using complex FFT's reduce the broadening of the center-burst and improve SNR
- De-jittering of frames of interferogram improved sharpness
- Channel masking before performing the Fast Fourier transform (FFT) reduces ringing
- Non-linearity correction minimizes spectral harmonics

A flexible FTS model



Parameters for simulations:

- 3 calibration sources at temperatures $T_0 = 20C$, $T_1 = 30C$ and $T_2 = 40C$, signal to noise ratio $SNR = 1000$, number of samples $N_f = 4096$ frames, and a responsivity between 750 and 1250 cm^{-1} (in-band).
- Phase dispersion model: $\phi(\nu) = 500\left(\frac{\nu}{\nu_{max}}\right)[1 + 0.3\left(\frac{\nu}{\nu_{max}}\right)^2]$
- Channeling amplitude: $amplitude(\nu) = (1. + 0.2 \cos(\omega_0\nu))$
- Nonlinear model: $DN(nonlin) = DN(lin)^d$ where $d = 0.33$
- Relative position sampling errors in sample units:
 - Periodic: $\Delta Z(z) = a_0 \sin(2\pi \frac{z}{\delta z})$
 - Random: $\Delta Z(z) = b_0 N(m = 0, \sigma = 1) \otimes LP - filter(cut-off = 0.1\nu_{max})$

where a_0 and b_0 are selected so that the standard deviation $STDEV(\Delta X)$ is 0.02 and 0.001 of a sampling distance.

Task:

Simulate the effect of phase errors, channeling and non-linearity on the 2-point calibration error on the measured black body (BB_1) using (BB_0) and (BB_2) measurements.

Two-point calibration

- Let $I_k(x, i, j)$ be the interferogram of the k -th calibration source at T_k .
- Let's define the measured spectral response (MSR) at the (i, j) pixel as:

$$MSR_k(\nu, i, j) = |FFT[I(x, i, j)]|.$$

- Given Planck's function $B()$, the calculated BB radiance for T_k is $CBB_k(\nu) = B(\nu, T_k)$.
- Assuming a linear detector the calibrated radiance $L_1(\nu)$ of BB_1 is:

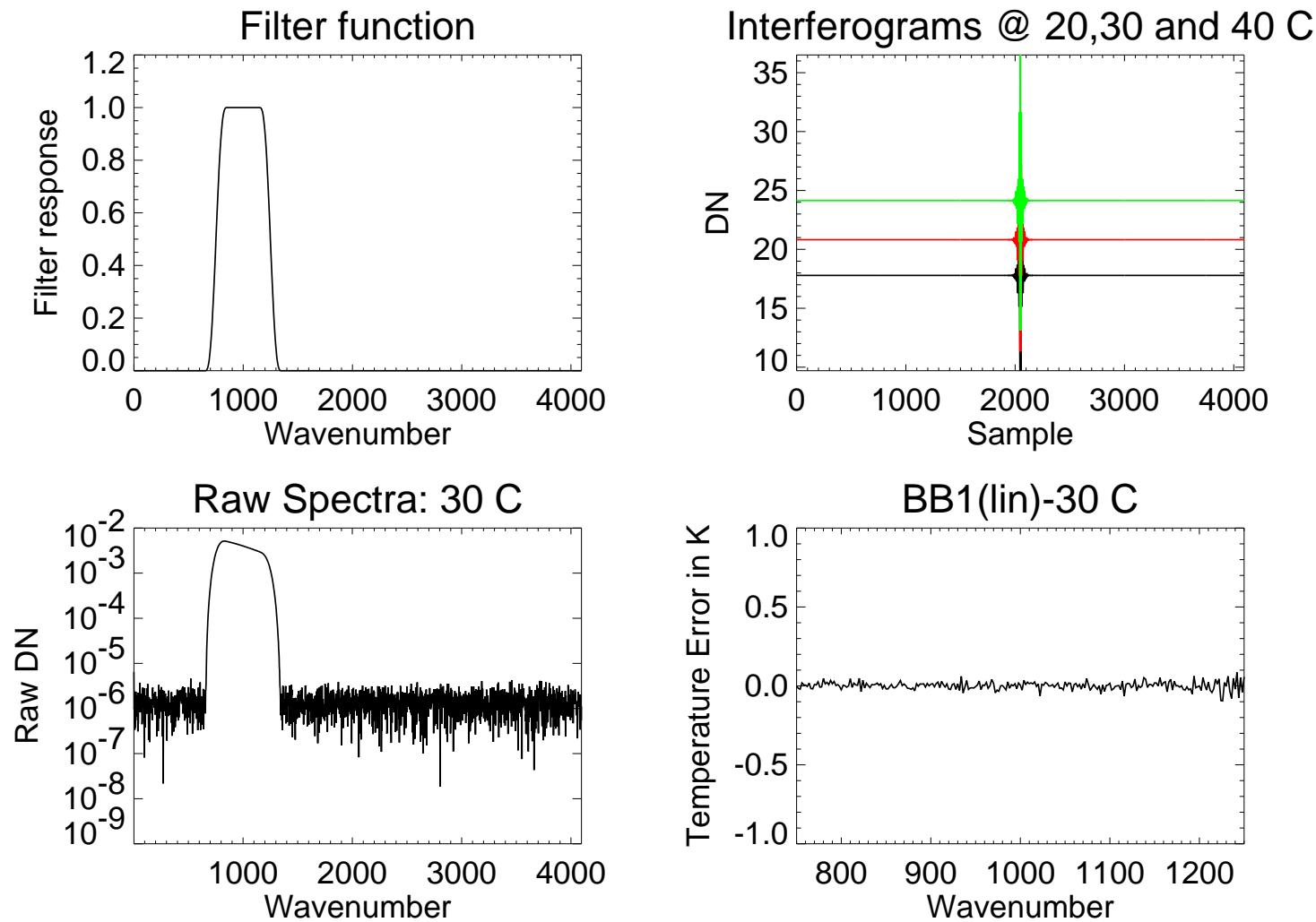
$$L_1(\nu) = \frac{MSR_1 - a(\nu, i, j)}{b(\nu, i, j)}$$

where

$$a(\nu, i, j) = MSR_0(\nu, i, j) - b(\nu, i, j)CBB_0(\nu), \text{ and}$$

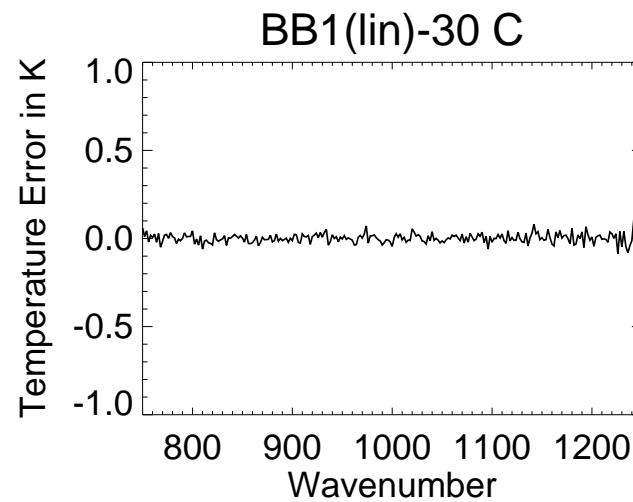
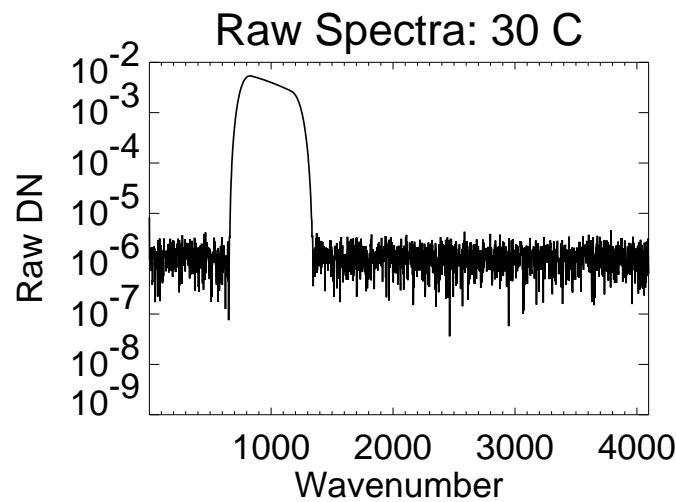
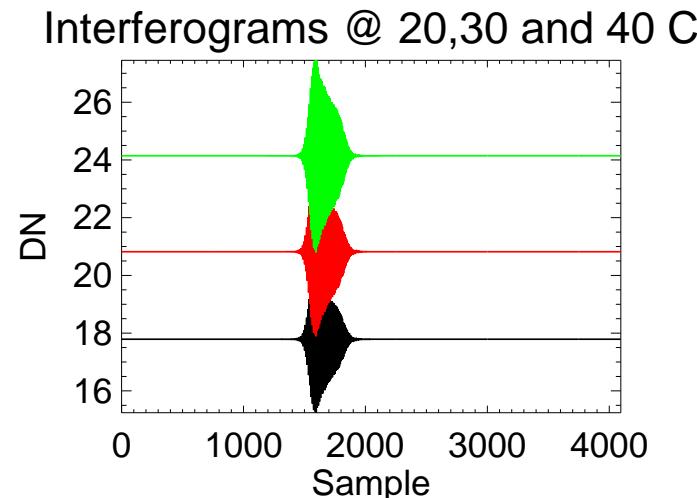
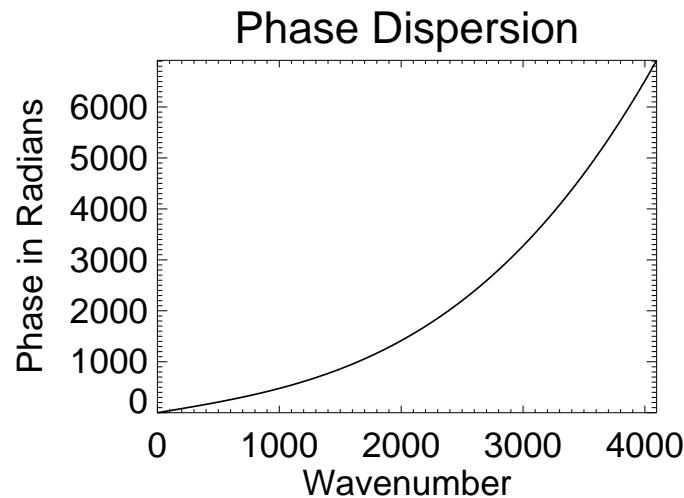
$$b(\nu, i, j) = \frac{MSR_2(\nu, i, j) - MSR_0(\nu, i, j)}{CBB_2(\nu) - CBB_0(\nu)}.$$

Linear FTS simulation



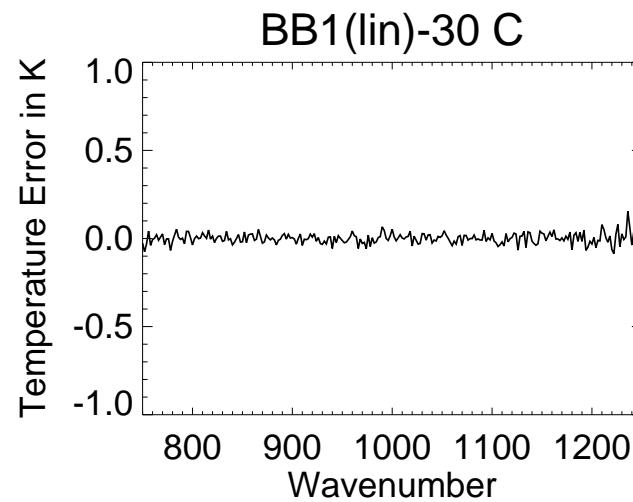
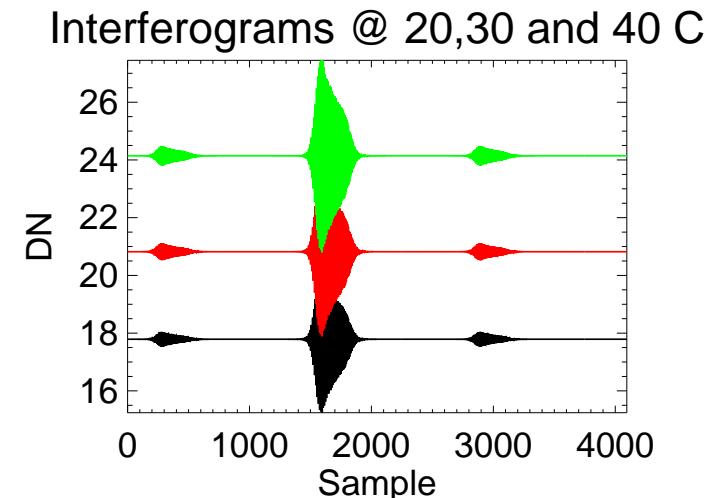
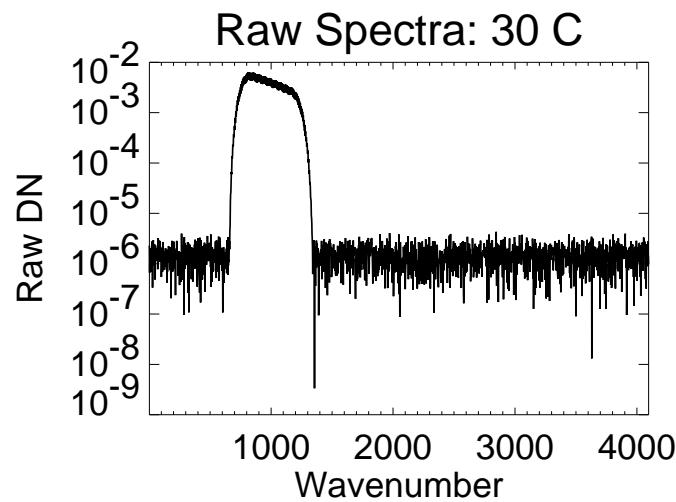
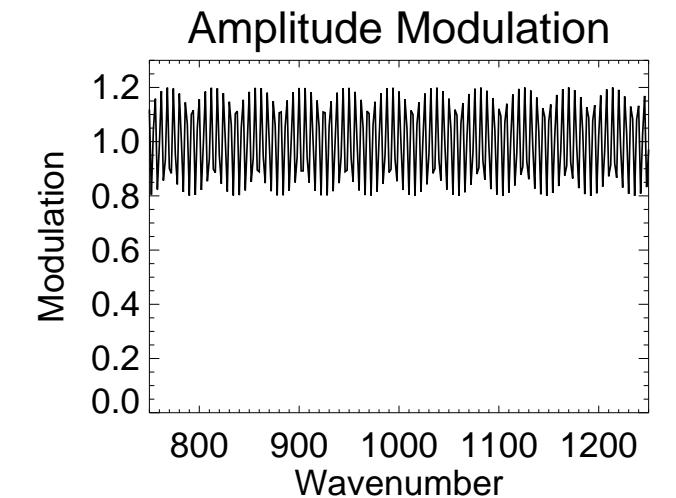
Note: The strongly peaked symmetric center-burst allows the acquisition of one-sided interferograms.

Linear + dispersion FTS simulation



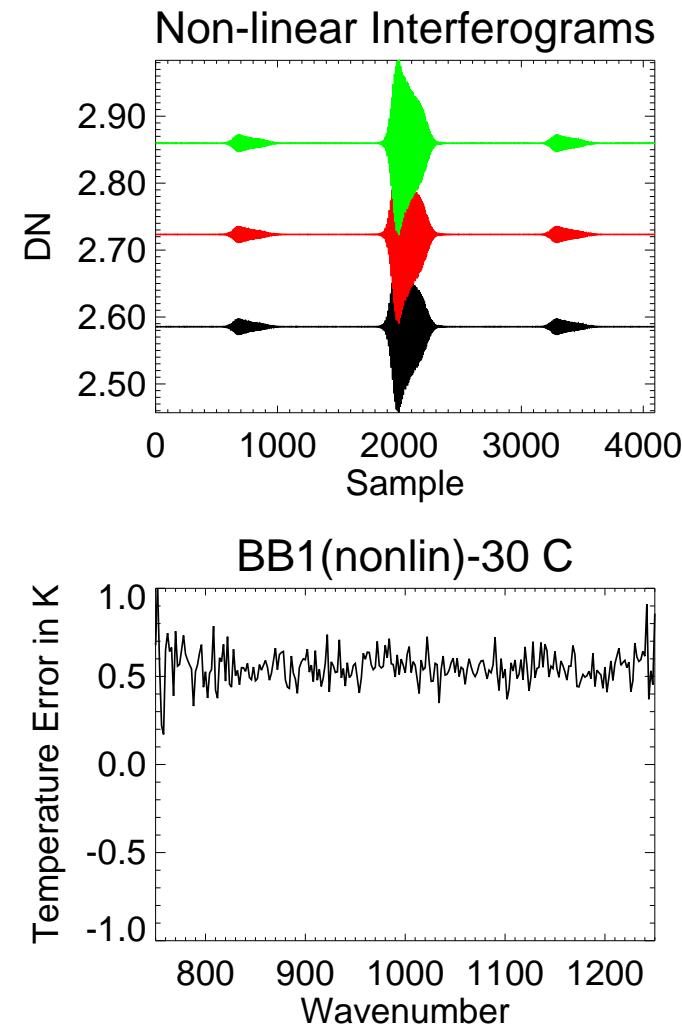
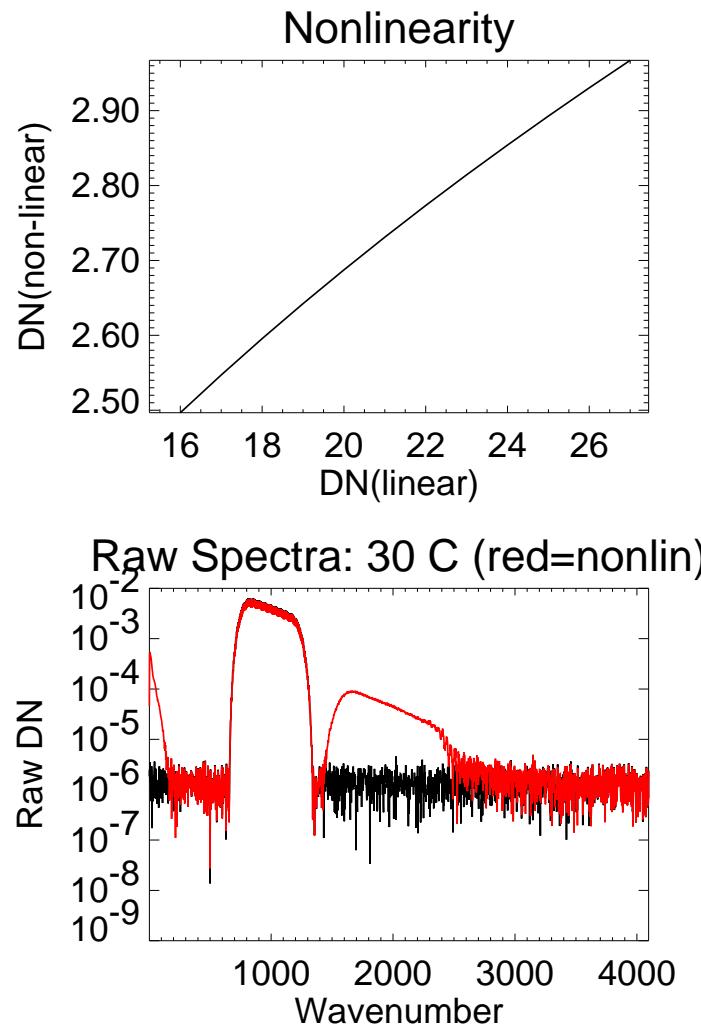
Notes: (1) The spread-out center-burst is asymmetric, thus two-sided interferograms need to be taken. (2) Dynamic range is reduced compared to the non-dispersed FTS.

Linear + dispersion + channeling FTS simulation



Note: Channeling causes ghosts of the center-burst. In the spectral domain the channeling manifests itself as amplitude modulations.

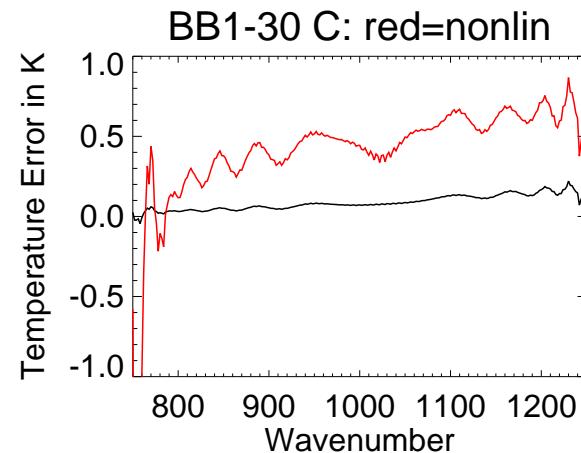
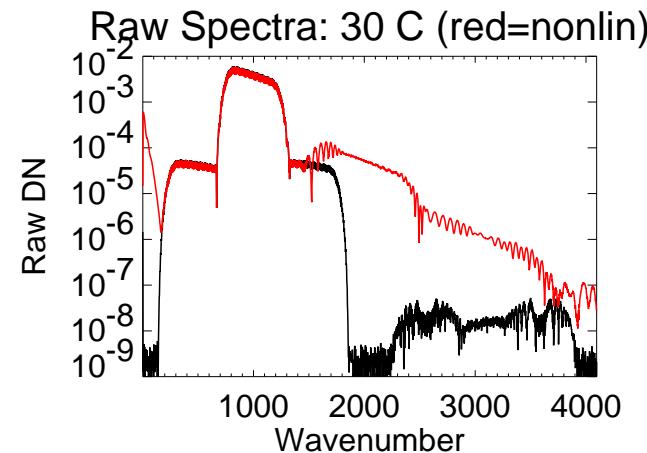
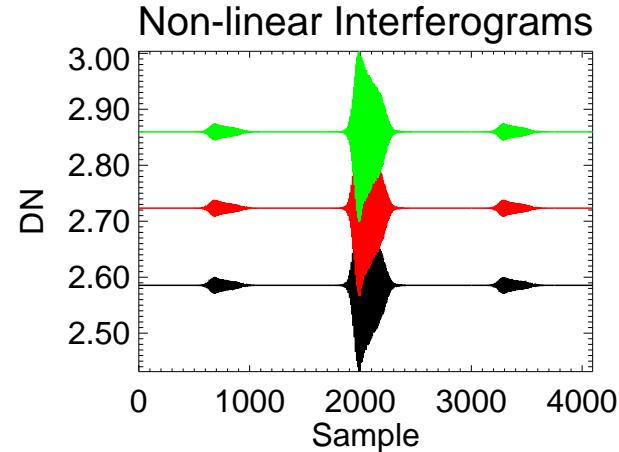
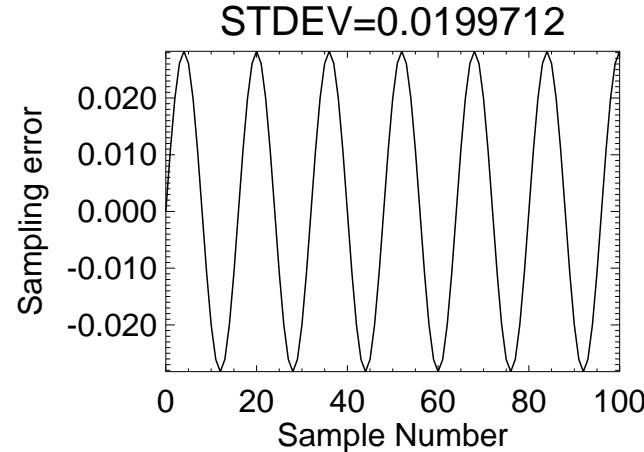
Non-linear + dispersion + channeling FTS simulation



Note: The spectral harmonics occur at the sum and differences of the in-band wavenumbers. There is a corresponding non-zero mean temperature offset on BB_1 and increased temperature noise compared to linear FTS's.

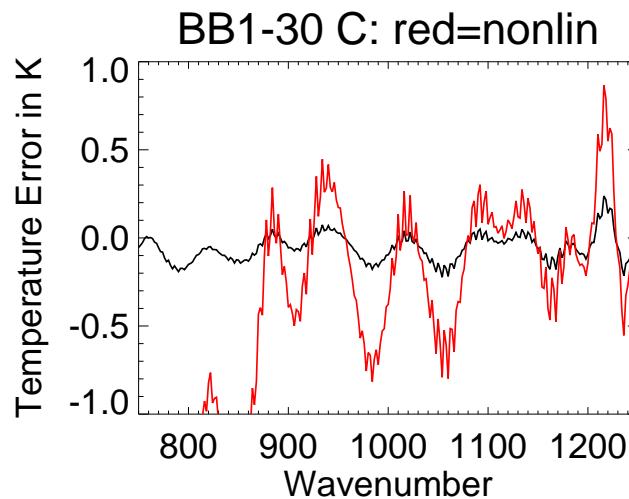
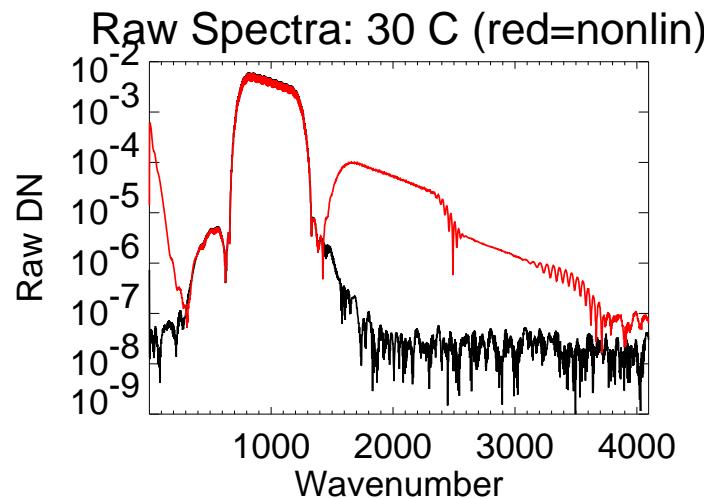
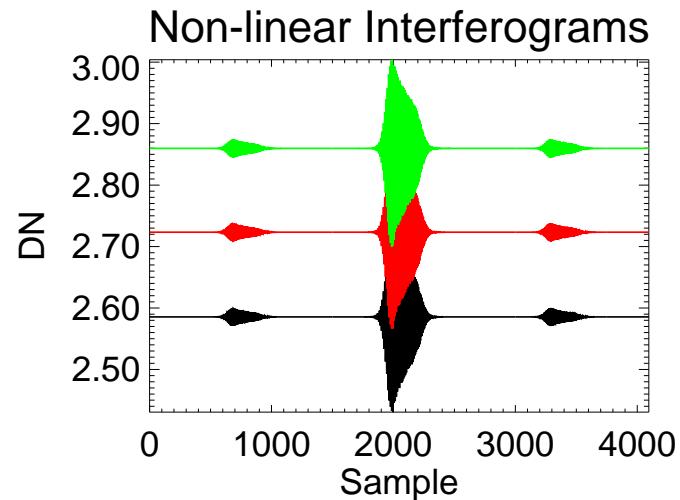
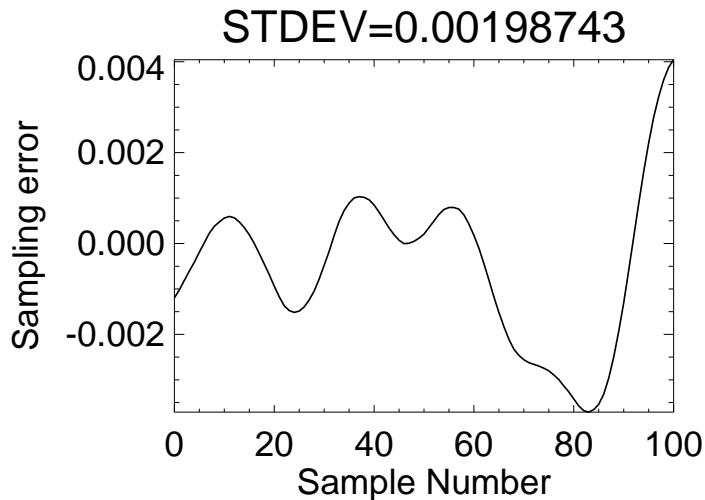
Non-linear + dispersion + channeling + sampling position error FTS simulation

Periodic sampling position error ΔZ and $SNR = \infty$: $\Delta Z(z) = a_0 \sin(2\pi \frac{z}{\delta z})$



Note: Temperature error consists of offset (for non-linear case only) and low-frequency components.

Random sampling position error and $SNR = \infty$: $\Delta Z(z) = b_0 N(m = 0, \sigma = 1) \otimes LP - filter(cut-off = 0.1\nu_{max})$



Note: Temperature error consists of offset (for non-linear case only) and low-frequency components.

Radiometric corrections

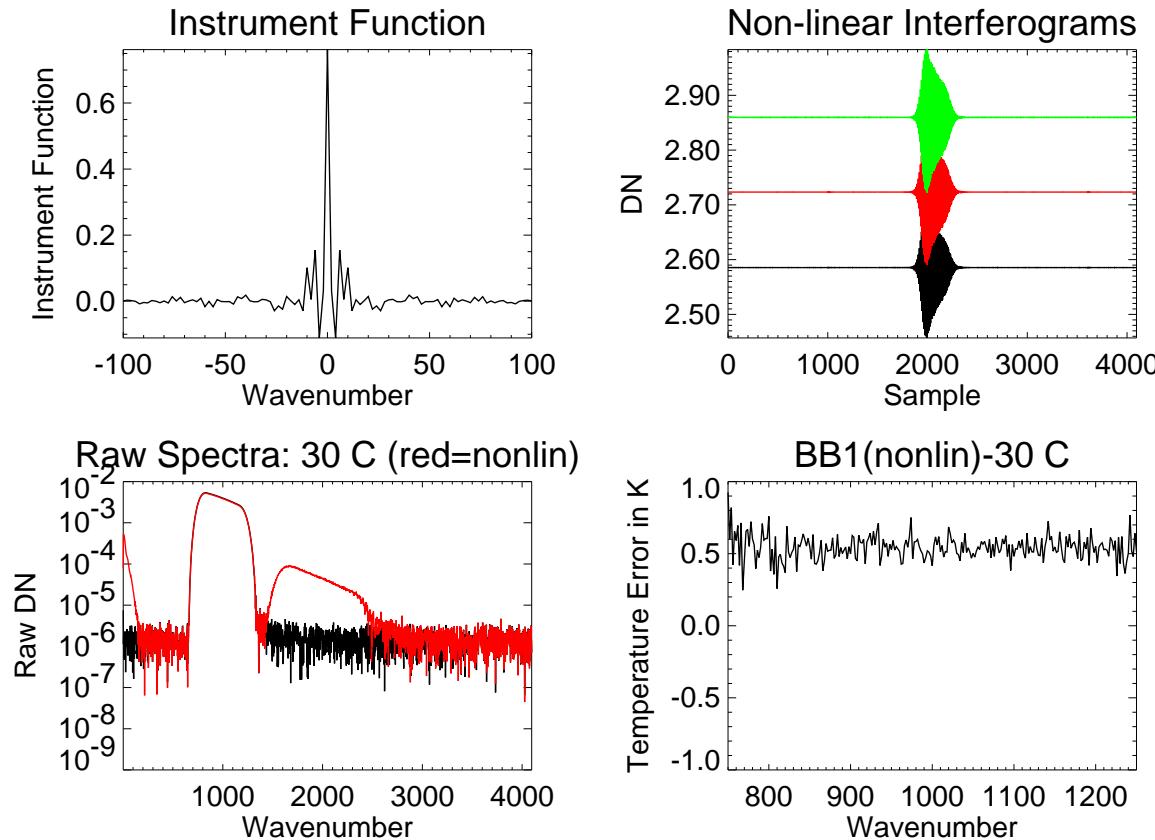
Phase error correction

Concept: Using a phase estimation technique it is possible to convert a dispersed interferogram into a non-dispersed interferogram.

Note: Experience with real FTS data shows that it is hard to achieve the theoretical improvement of $\sqrt{2}$.

Channeling effect correction

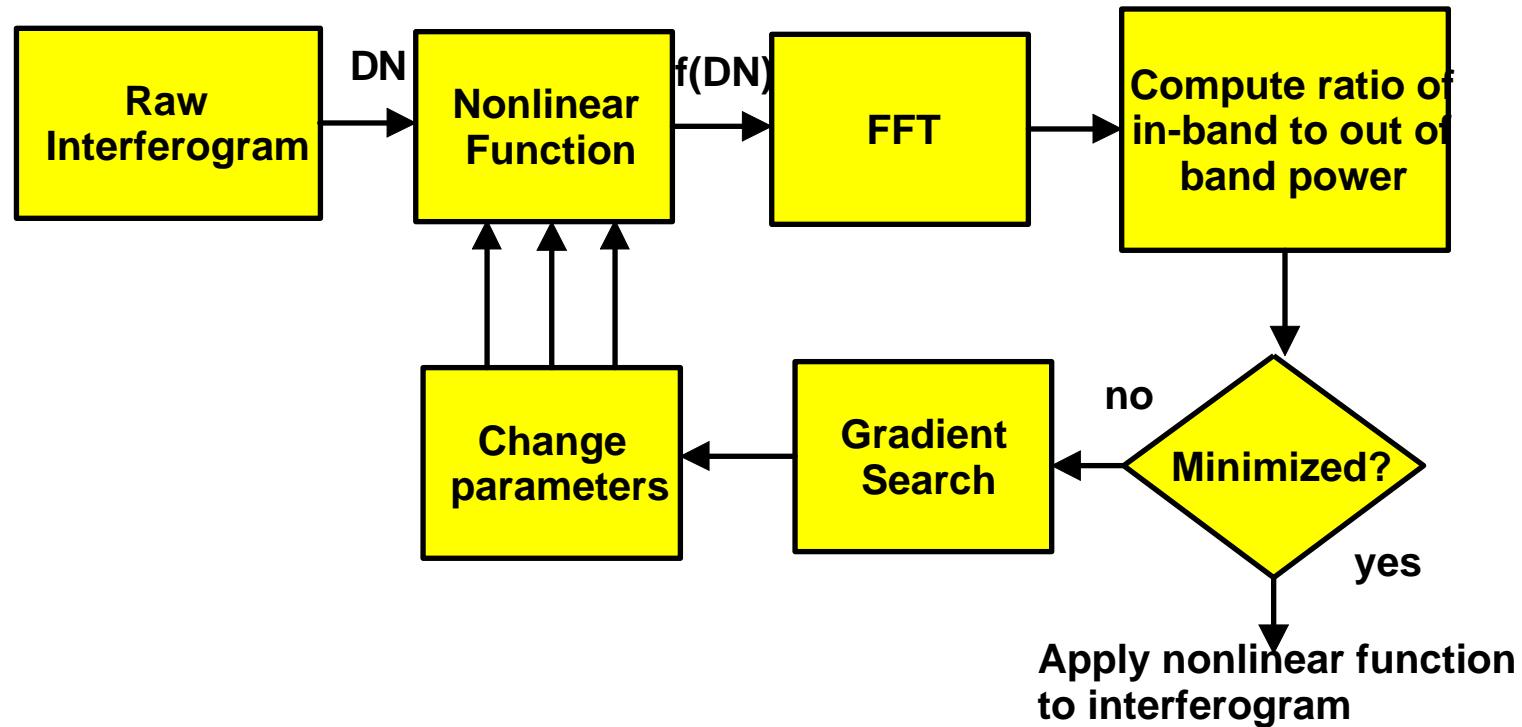
Concept: Cutting off (apodizing) of the channeling bursts removes the strong oscillation in the spectral domain.



Notes: (1) Apodizing the channeling bursts eliminates the sinusoidal modulation in the spectral domain. (2) Removing the channeling, however, introduces instrument functions with side lobes (see figure) which introduce ringing near narrow spectral features, e.g. atmospheric absorption lines.

Non-linear response correction

Concept to correct nonlinear detector response

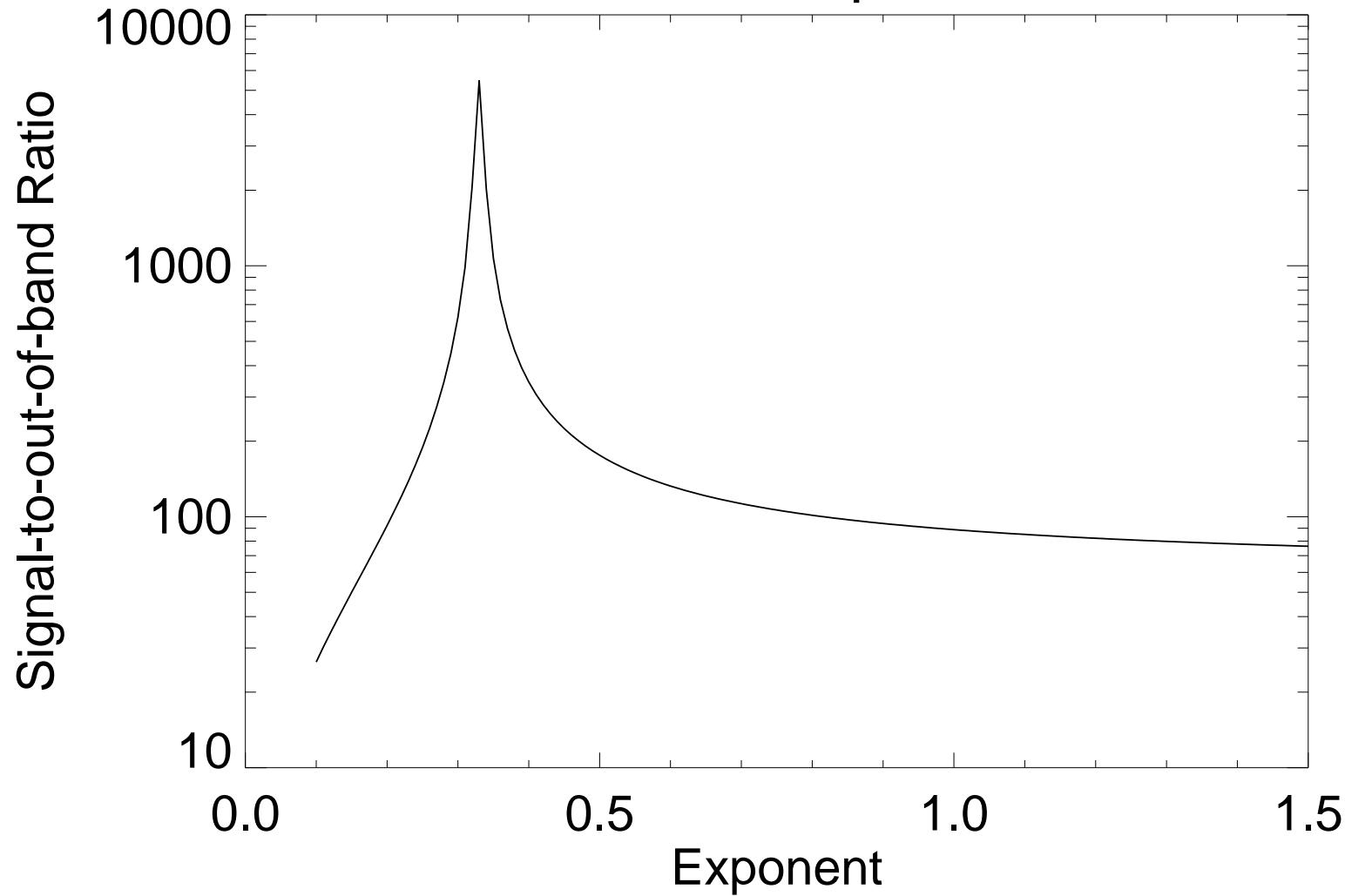


Retrieval of the exponent d for the non-linear model $y = x^d$ is achieved by maximizing the ratio:

$$R = \frac{\max\{In-band\ Signal\}}{\sigma\{Out-of-band\ Signal\}}$$

, where the *In – band* is from 750 to $1250\ cm^{-1}$.

Retrieval of NL parameter



Note: The exponent $d = 0.33$ for the nonlinearity $y = x^d$ was correctly identified.

Geometric corrections

Problem:

Given a reference image $I(0)$ and a sequence of N x/y shifted and rotated images find the optimal shifts, $x_{opt}(n)$ and $y_{opt}(n)$ and rotation, $\phi_{opt}(n)$, to minimize:

$$RMSE(I(0) - \text{rotate}(\text{shift}(I(n)), x_{opt}(n), y_{opt}(n)), \phi_{opt}(n))).$$

Possible Algorithms:

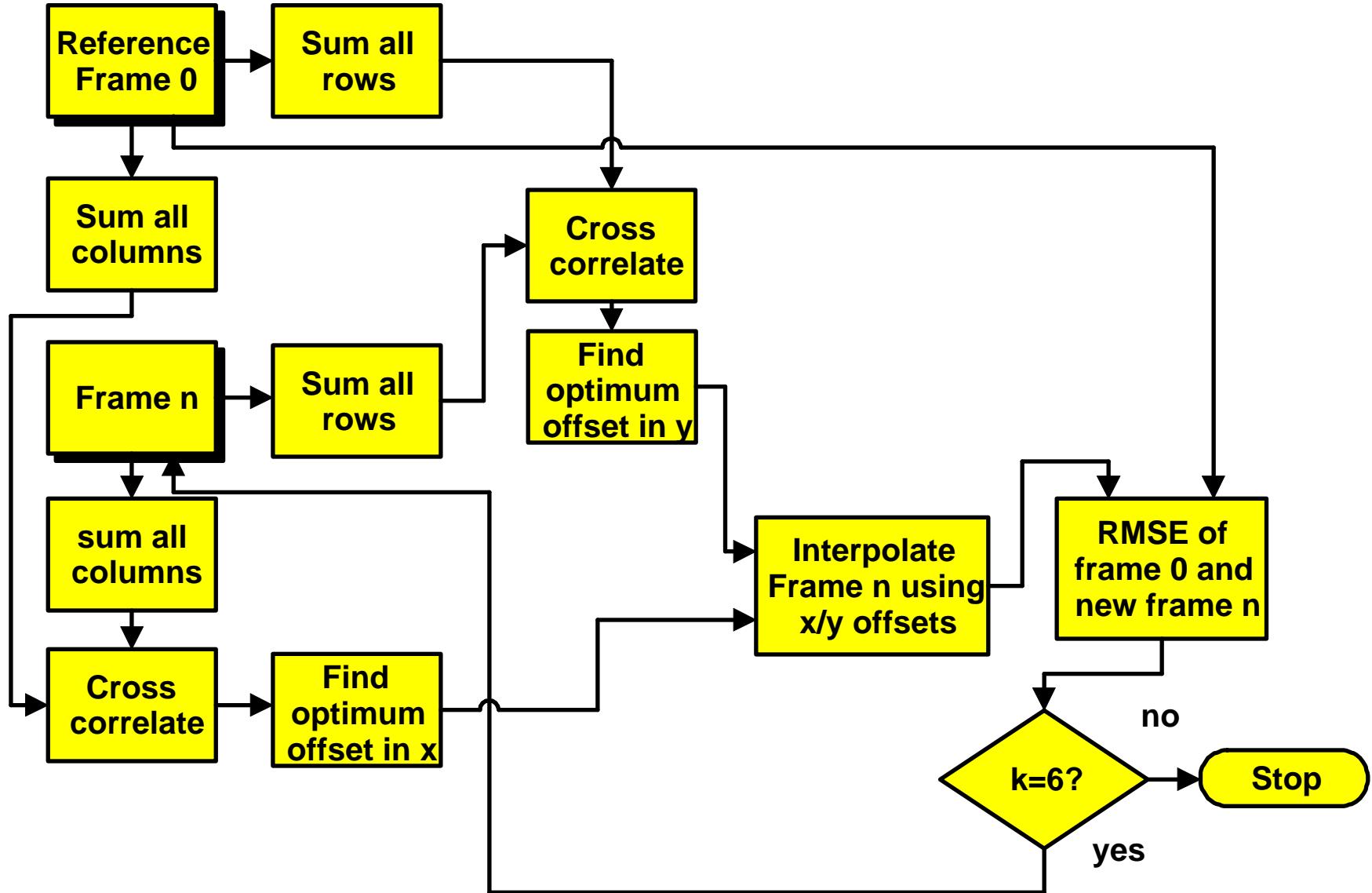
1. Direct 3-D cross correlation to find x/y shifts and rotation.
2. Direct 2-D cross correlation to find x/y shifts
3. Adaptive (from low resolution to high-resolution) 2-D image correlation
4. Reduce problem to separable 1-D correlations to also handle rotations

Advantages of 4 over 1-3:

- Perform simple 1-D correlations rather than computationally expensive 2 or 3-dimensional.
- Methods 2 and 3 only work for shifts.

Fast x/y shift determination

Block diagram for a fast tracking algorithm:



Steps:

1. Initialize a maximum search range R_0 , e.g. $+/- 5$ pixels
2. Sum over all rows and columns of reference frame to obtain 1-D vectors $S_x(0) = \sum_x(I(0))$ and $S_y(0) = \sum_y(I(0))$.
3. For frame n and k iterations do:
 - (a) Let $x_{opt,0}(n) = x_{opt}(n - 1)$ and $y_{opt,0}(n) = y_{opt}(n - 1)$
 - (b) Cross-correlate 1-D vectors over a range of shifts from $-R$ to R in 11 steps:

$$S_x(n) = \sum_x(\text{shift}(I(n), x_{opt}(n - 1), y_{opt}(n - 1))), \text{ and}$$

$$S_y(n) = \sum_y(\text{shift}(I(n), x_{opt}(n - 1), y_{opt}(n - 1)))$$

with $S_x(0)$ and $S_y(0)$ to find residual shifts δ_x and δ_y which minimize $\text{RMSE}(S_x(0) - \text{shift}(S_x(n), \delta_x, \delta_y))$ and $\text{RMSE}(S_y(0) - \text{shift}(S_y(n), \delta_x, \delta_y))$.

- (c) Let $x_{opt,k}(n) = x_{opt,k-1}(n) - \delta_{x,k-1}$ and $y_{opt,k}(n) = y_{opt,k-1}(n) - \delta_{y,k-1}$
- (d) Reduce the range by $R_k = R_{k-1}/2$

Fast rotation determination

Steps:

1. Initialize a maximum search angle range for Φ_0 , e.g. +/- 5 degrees
2. Sum over all rows and columns of reference frame to obtain 1-D vectors $S_x(0) = \sum_x(I(0))$ and $S_y(0) = \sum_y(I(0))$.
3. For frame n and k iterations do:
 - (a) Let $\phi_{opt,0}(n) = \phi_{opt}(n - 1)$
 - (b) Cross-correlate 1-D vectors over a range of angles from $-\Phi$ to Φ in 11 steps:

$$S_x(n) = \sum_x(\text{rotate}(I(n), \phi_{opt}(n - 1))), \text{ and}$$

$$S_y(n) = \sum_y(\text{rotate}(I(n), \phi_{opt}(n - 1)))$$

with $S_x(0)$ and $S_y(0)$ to find residual rotation angle $\delta\phi$ which minimize $RMS E(S_x(0) - \text{rotate}(S_x(n), \delta\phi))$.

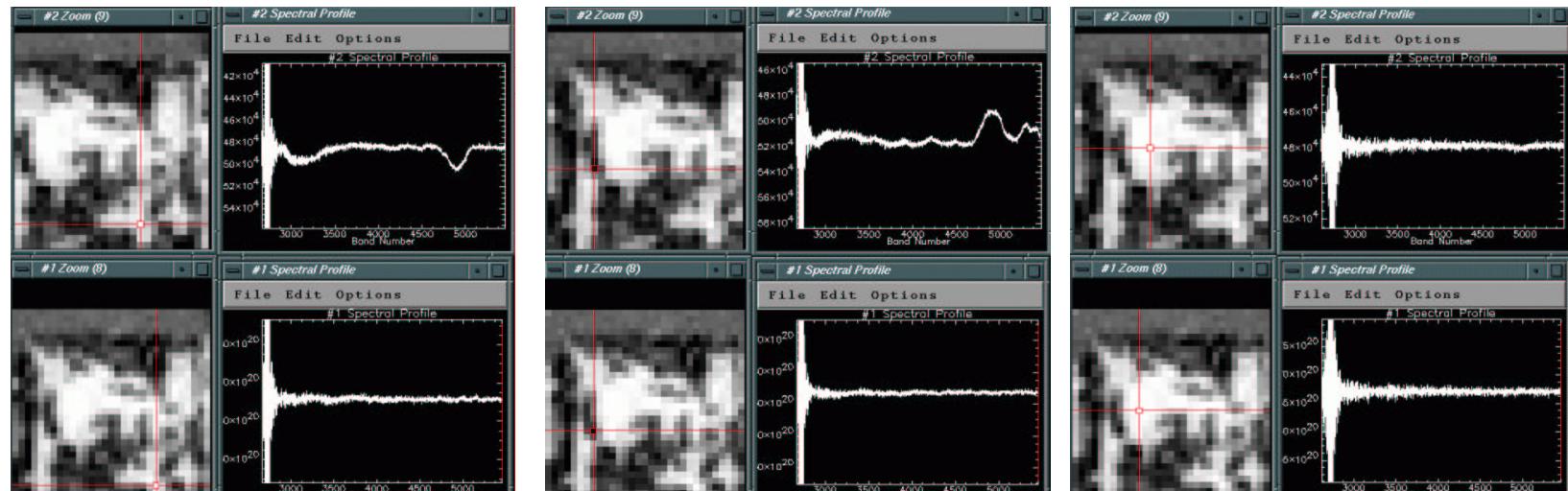
- (c) Let $\phi_{opt,k}(n) = \phi_{opt,k-1}(n) - \delta\phi_{k-1}$
- (d) Reduce the angular range by $\Phi_k = \Phi_{k-1}/2$

Effect of jitter

Effect of jitter depends on the surrounding area:

- A bright pixel surrounded by dark pixels shows strong base line shifts
- A dark pixel surrounded by bright pixels shows strong base line shifts
- A pixel in a uniform region shows no baseline shifts

Effect of Jitter Restoration on Pixels near Contrasts (a,b) and in uniform Regions (c) shown in the FTIR data cube



Bright Pixel

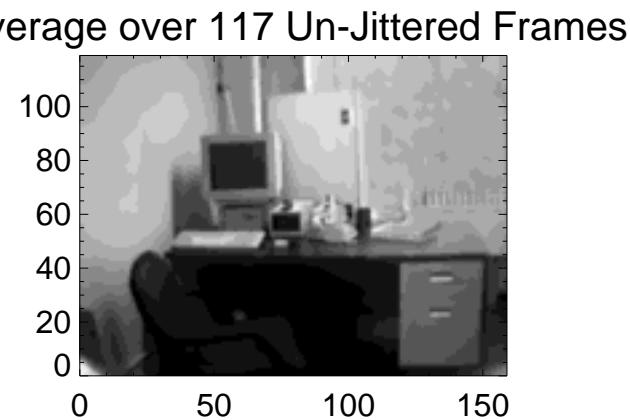
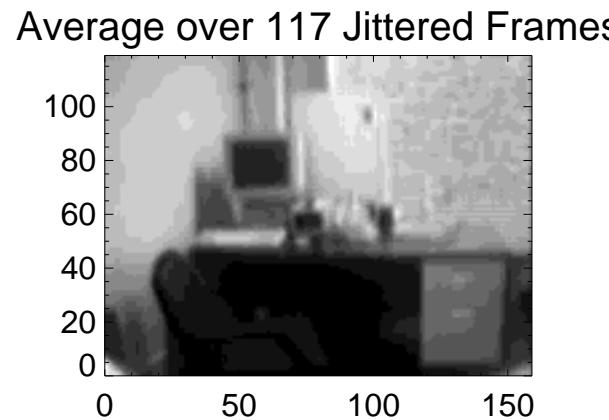
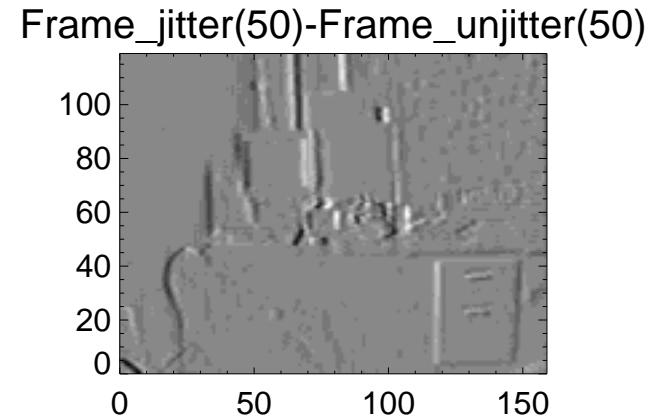
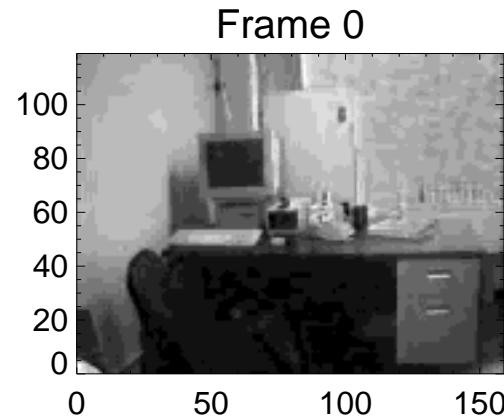
Dark Pixel

Uniform Pixel

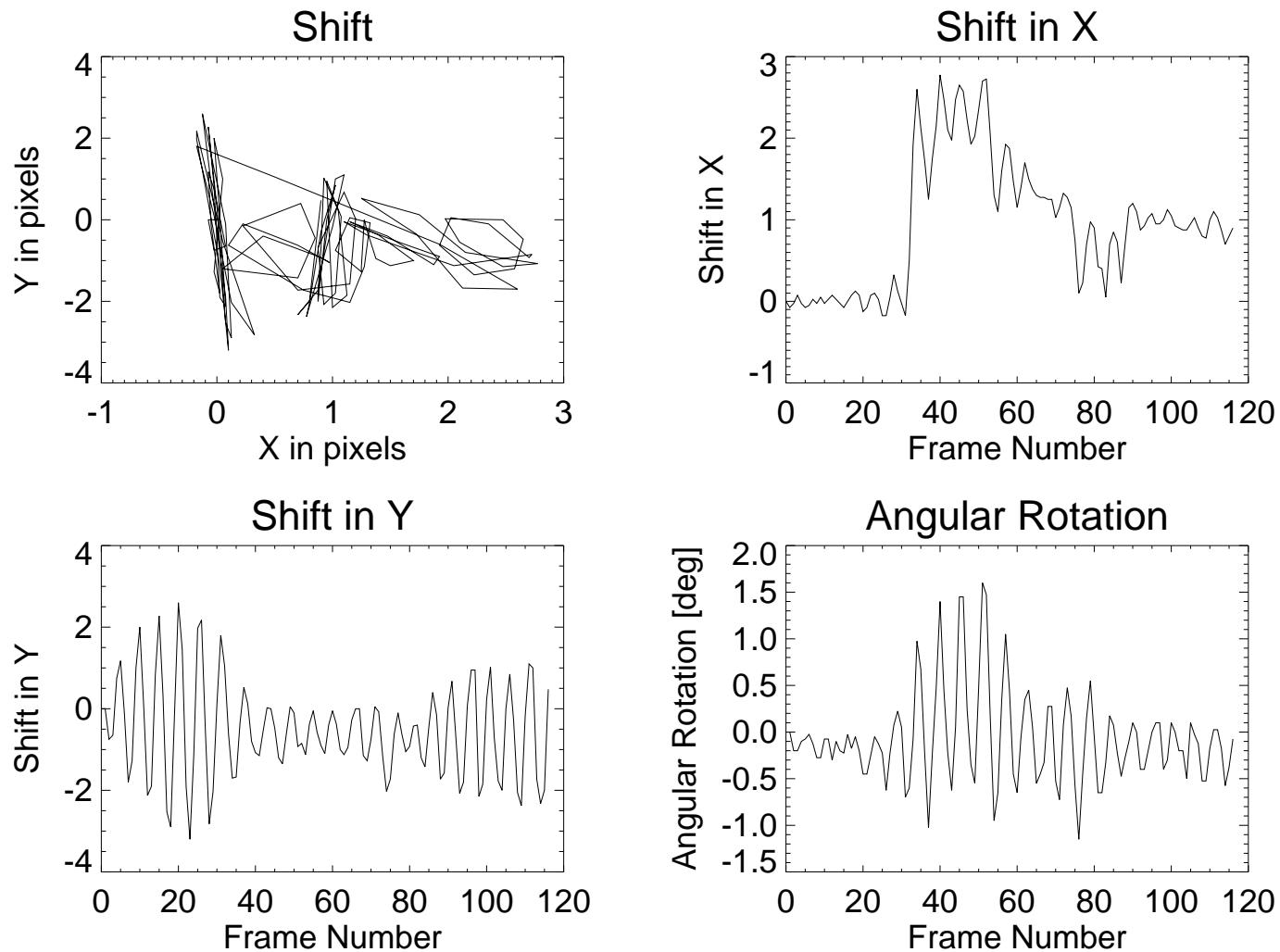
Results

Experiment 1: Recorded 117 frames of video from camera placed on a shaking surface and tracked shifts and rotations

Effect of jitter and de-jittering on overall image quality:



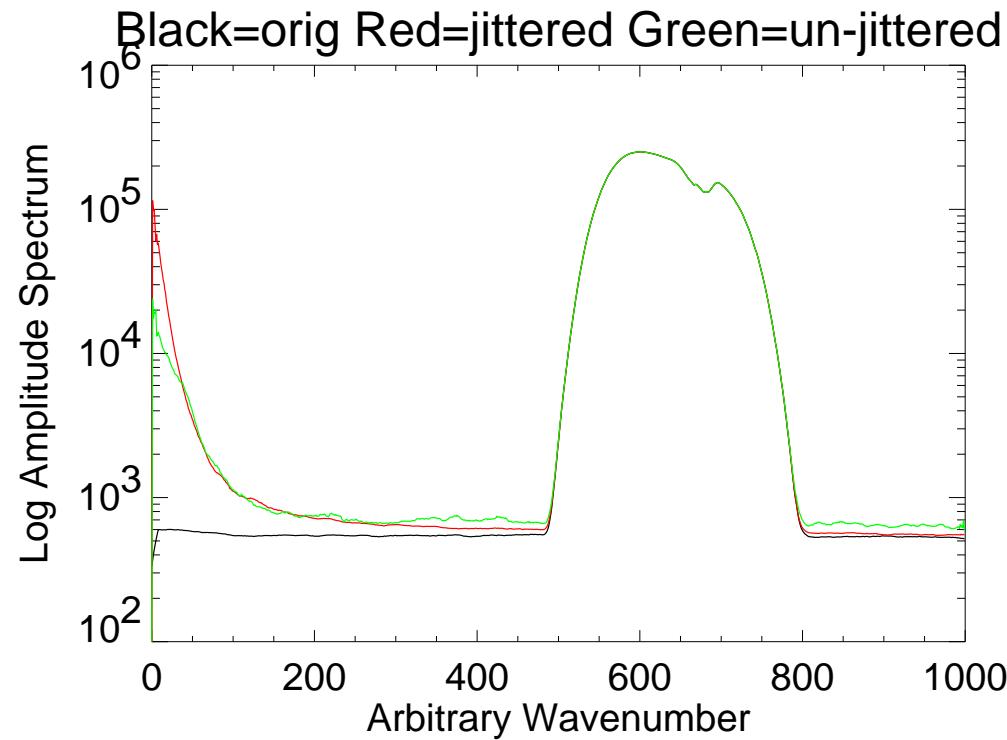
Results of tracking for video sequence:



Note: It is difficult to obtain both (shift and rotation) estimates. Avoid image rotations if possible!

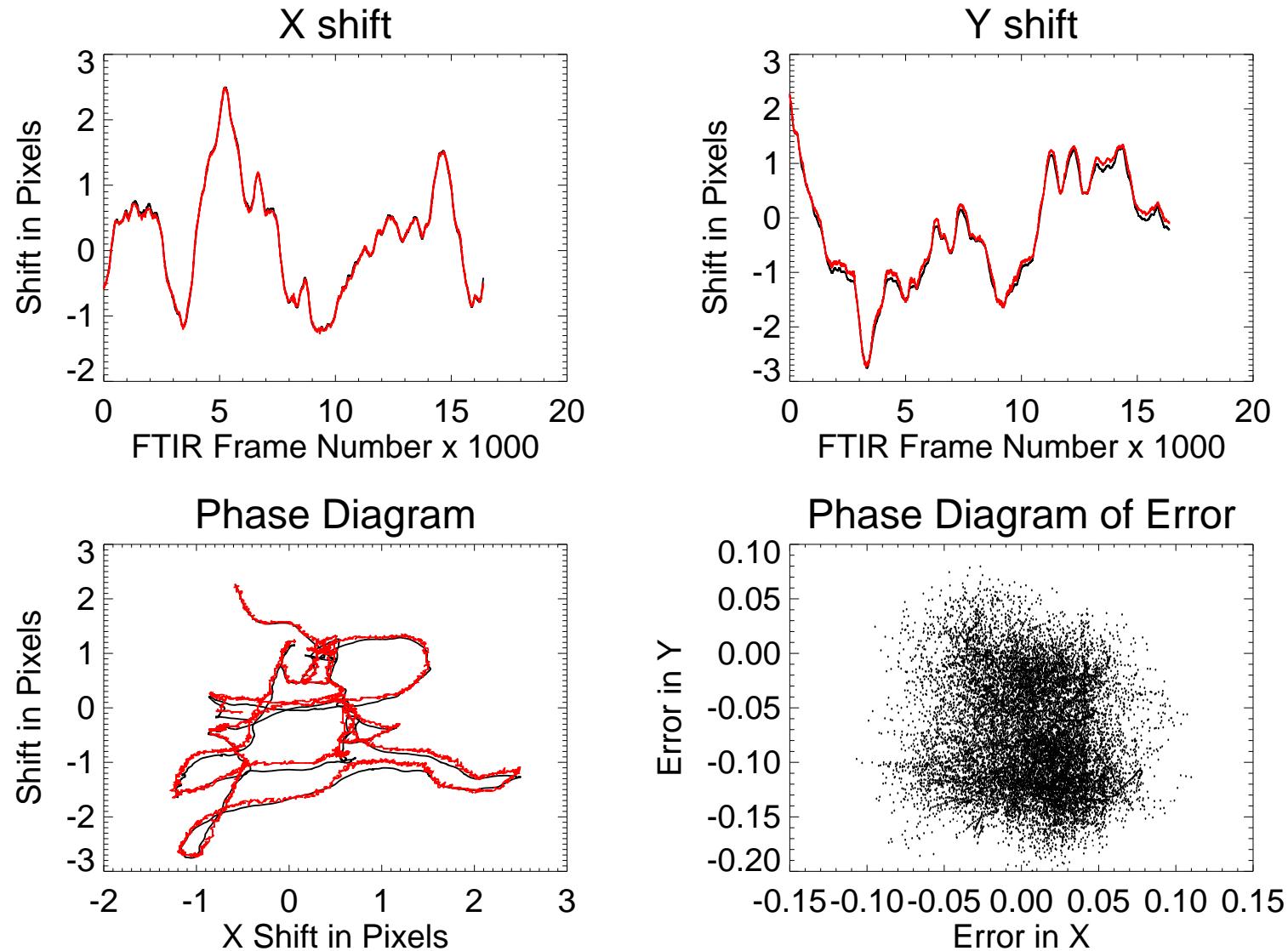
Experiment 2: Track motions in a simulated FTS cube Steps:

1. Generate a simulated linear FTS image cube C_0 and jitter each frame of the cube using a known jitter function $x_{off}(n)$ and $y_{off}(n)$ to obtain a cube C_j .
2. Perform de-jittering of cube and store result in C_u .
3. Fourier transform C_0 , C_j and C_u and compute the average spectra over a region of 32×32 pixels



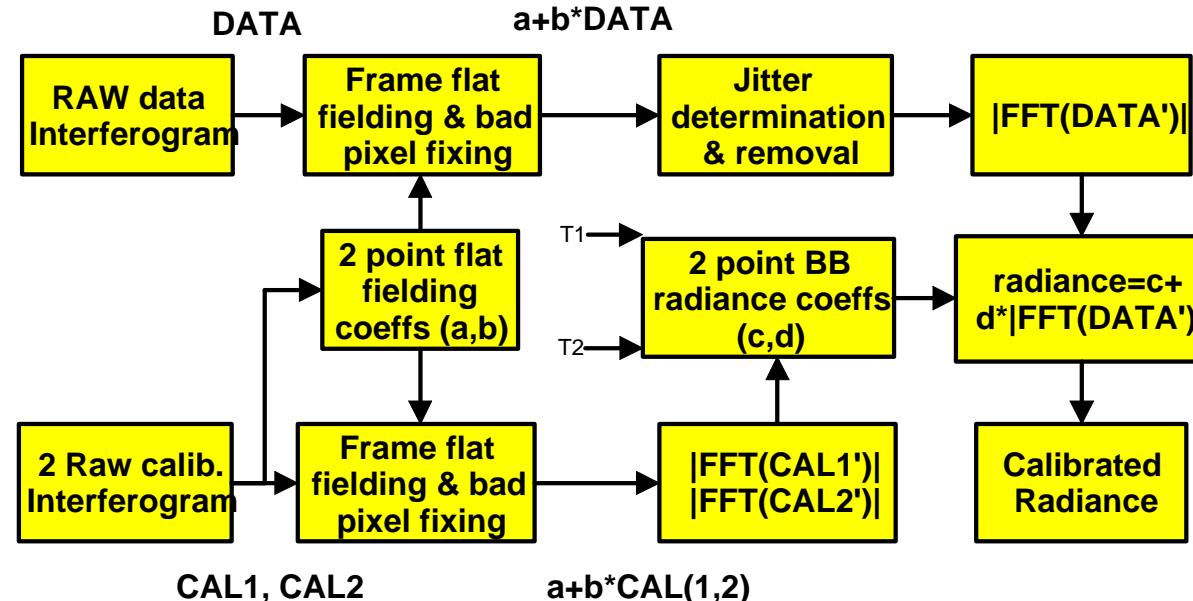
Note: The de-jittering process has little effect on the spectral region of interest (500-800 arbitrary wavenumbers) but reduces the spurious signal near zero wavenumber.

Experiment 3: Results of tracking motions in a simulated FTS cube:



Note: The tracking error for shifts only is less than one 10-th of a pixel.

FTIR Data Calibration Scheme



Notes:

- A frame flat fielding of the data cube is performed in the interferogram domain using 2 calibration cubes to eliminate pixel artifacts from different gains and offsets and allow jitter determination.
- Bad pixel fixing steps:
 1. Find "bad pixels" = "dead" pixels and "noisy" pixels
 2. Grow a region around "bad pixels" using a cross shaped kernel
 3. Delauney triangulation of neighbor pixels and quintic interpolation at bad pixels
- A two-point calibration is performed in the spectral domain.

Data compression

Facts:

- System spectral response is usually band limited (e.g. $8\text{-}12 \mu\text{m}$ band).
- Only a fraction ($1/8$ th) of the spectral image cube is retained after the FFT which is a $N \log N$ complex operation.

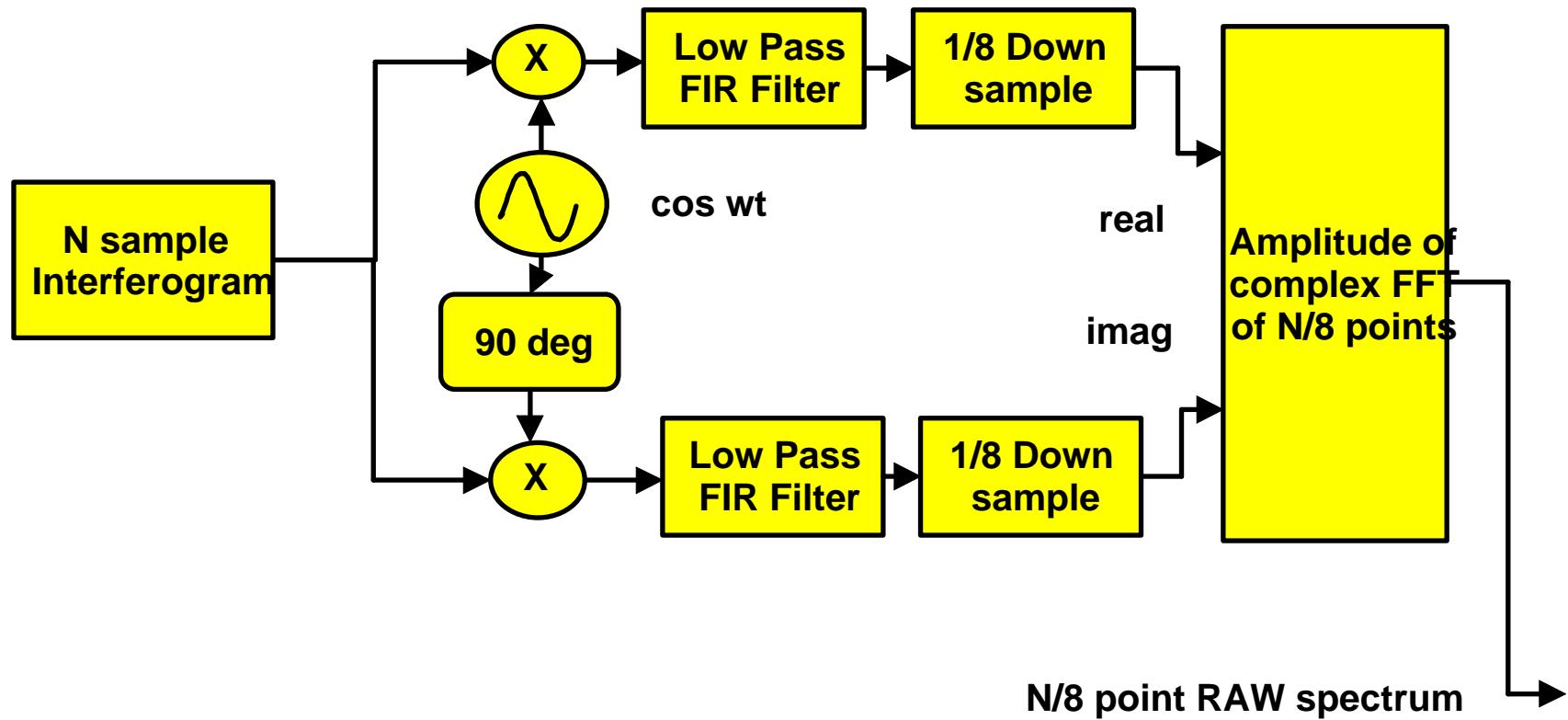
Problem: Find a solution to reduce the number of operations necessary to generate the spectral cube and save storage space for the raw data.

Solution Steps:

1. Modulate the interferogram with a carrier using Sine and Cosine
2. Convolve modulated interferogram with a low-pass filter
3. Down-sample the resulting in-phase and quadrature phase signals to $1/8$ the number of samples.
4. Perform a complex FFT and store the amplitude of the result.

Note: This is a heterodyne receiver!

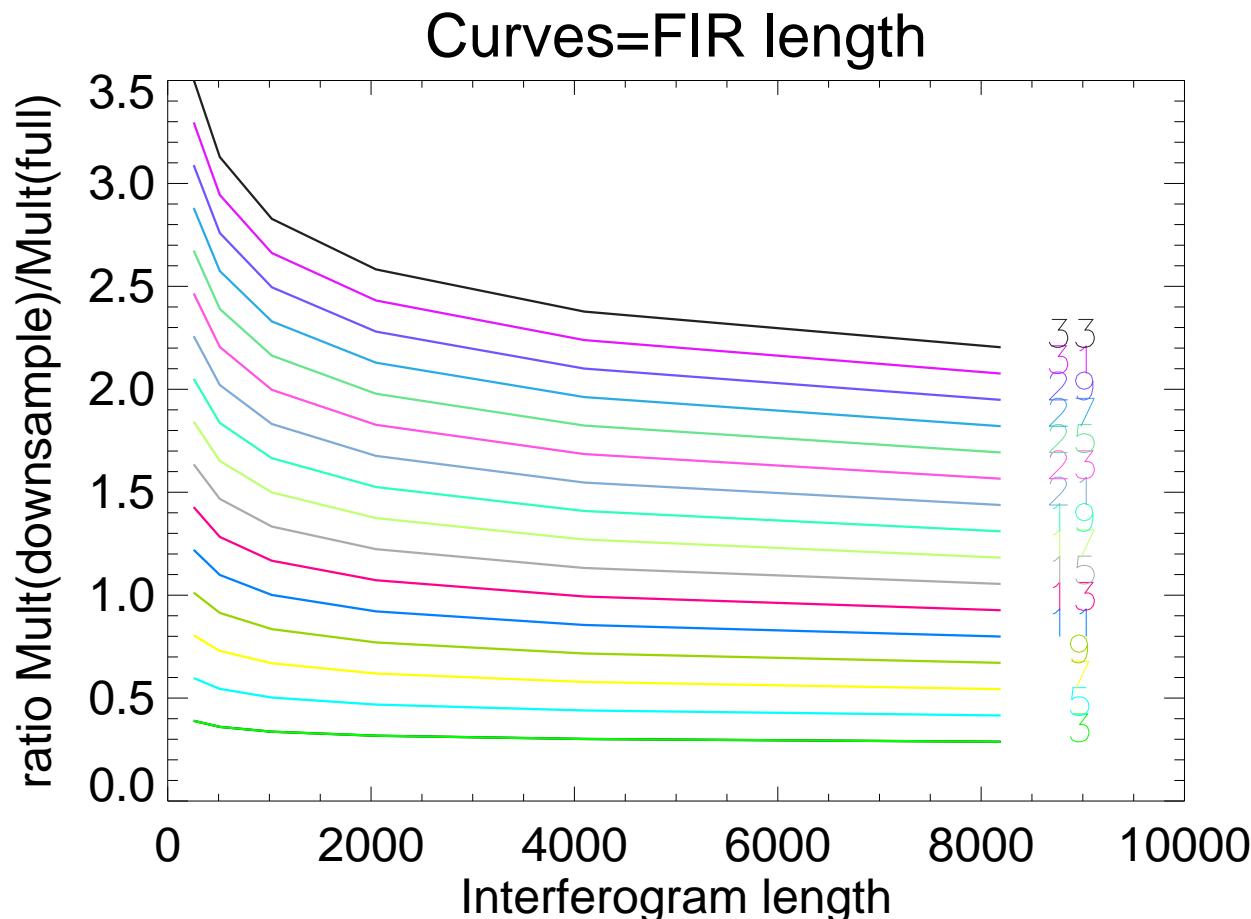
Down Sampling of FTIR Data to 1/8 of Original Number of Samples



Problem: Compute ratio of the number of multiplications required for a reduced FFT with down-sampling over the number required for a full FFT a function of interferogram length N and finite-impulse-response (FIR) length L .

Solution:

$$R = \frac{N/8 \log_2 N/8 + 2N/8L}{N \log_2 N}.$$



Conclusions

Several “real world” effects on FTS data have been presented and some methods to reduce their effect:

- Channeling removal by apodizing the interferogram introduces ringing near spectral lines **or** calibrated out given a sufficiently stable FTS system.
- Jitter removal improves image sharpness but has little effect on spectral fidelity if the jitter is low-frequency.
- Non-linearity correction eliminates systematic calibration errors.
- Heterodyne and down-sampling processing reduces the number of operations to generate the spectral cube and storage requirements.
- Special care must be taken to eliminate sampling errors if the detector is non-linear.

References

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- Peter R. Griffiths and James A. de Haseth, Fourier transform infrared spectrometry, xv, 656 p., New York, Wiley, 1986.
- Bennett, C.L., LIFTRS, the Livermore imaging FTIR, Conference on Fourier transform spectroscopy, 11., p.170-186, 10-15 Aug, 1997. Online at:
<http://www.llnl.gov/tid/lof/documents/pdf/231514.pdf>
- A very nice introduction in French to Michelson interferometers can be found at:
<http://www.sciences.univ-nantes.fr/physique/enseignement/tp/michelson/michp.html>
- A nice write-up by Paul Van Delst on correcting HgCdT non-linearities for the AERI instrument can be found at:
http://airs2.ssec.wisc.edu/~paulv/aeri/aerinsa_nlanalysis/971113b1/971113b1.html
- Software to perform jitter correction using a hierarchical cross-correlation technique can be found at:
<http://idlastro.gsfc.nasa.gov/ftp/contrib/varosi/vlib/>
- The PostScript version of this talk will be available on:
<http://nis-www.lanl.gov/~borel>